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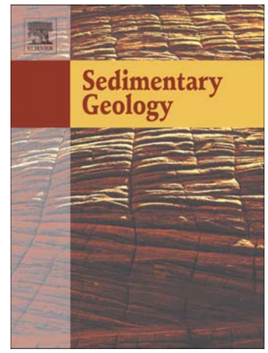

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Magnitudes of nearshore waves generated by Tropical Cyclone Winston, the strongest landfalling cyclone in South Pacific records. Unprecedented or unremarkable?

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Abstract

We delimit nearshore storm waves generated by category-5 Tropical Cyclone Winston in February 2016 on the northern Fijian island of Taveuni. Wave magnitudes (heights and flow velocities) are hindcast by inverse modelling, based on the characteristics of large carbonate boulders (maximum 33.8 m^3, 60.9 metric tons) that were quarried from reef-front sources, transported and deposited on coral reef platforms during Winston and older extreme events. Results indicate that Winston's storm waves on the seaward-margin of reefs fringing the southeastern coasts of Taveuni reached over 10 m in height and generated flow velocities of 14 m s^{-1}, thus coinciding with the scale of the biggest ancient storms as estimated from pre-existing boulder evidence. We conclude that although Winston tracked an uncommon path and was described as the most powerful storm on record to make landfall in the Fiji Islands, its coastal wave characteristics were not unprecedented on centennial timescales. At least seven events of comparable magnitude have occurred over the last 400 years.

Keywords: coastal boulders; extreme waves; wave magnitude; Cyclone Winston; South Pacific; tropical cyclones

1. Introduction

1.1 Understanding disaster risk from tropical cyclones

The Sendai Framework for Disaster Risk Reduction 2015-2030 (UNISDR, 2015), adopted by the United Nations in 2015, places 'understanding disaster risk' as the first priority in the global task of substantially reducing the human cost of disasters over the coming decades. Embedded in the first priority is the need to understand the characteristics of hazards. In the tropical South Pacific basin, tropical cyclones are one of the main natural hazards that occur with an annual frequency. Much has undeniably been learnt concerning the patterns and behaviour of tropical cyclones in the South Pacific (e.g., Basher and Zheng, 1995; Kuleshov et al., 2008; Terry and Gienko, 2010; Dowdy et al., 2012; Diamond et al., 2013). Dealing with cyclones nonetheless remains a great challenge for Pacific Islands nations (Magee et al., 2016).

Over recent years, a number of particularly devastating tropical cyclones has impacted various island nations, including Heta, Pam and Winston that struck Niue, Vanuatu, and Fiji respectively in 2004, 2015 and 2016. These cyclones surpassed previous records for their widespread destruction in the islands they afflicted. This paper focuses on Cyclone Winston, currently ranked third most intense cyclone to form in the South Pacific basin and one of the most powerful systems ever recorded in the southern hemisphere (FMS, 2016b). Winston is remarkable for making history by becoming the first cyclone to make landfall in the Fiji Islands as a category-5 system and is the most severe cyclone to make landfall in the South Pacific (FMS, 2016c; WMO, 2016) (Fig. 1). A state of emergency was declared after extensive ruin was inflicted across Fiji, with 40,000 houses damaged or destroyed. Costs of damage have been estimated at FJD 2.98 billion (USD 1.4 billion); Winston was therefore the costliest ever cyclone for the Fiji Islands. Close to 40% of the nation's population (350,000 people) was impacted in a significant way (WMO, 2016). Fatalities numbered 44.

High-magnitude but low-frequency cyclone events pose a concern for coastal vulnerability. An important question in the aftermath of Winston is whether such a storm represents the upper limit of cyclone intensity to be anticipated in Fiji, or have events of greater magnitude been experienced in the past? Such questions are not easy to answer. Satellite observations of tropical cyclones only stretch back to the 1970s. This provides a limited dataset for empirical analysis. Unknown stronger storms may have occurred before the modern satellite record began. In addition, little information on wave height and power is available. But the majority of the Pacific Island populations lives on the coast, and is therefore especially at risk from marine flooding. Although a combination of satellite altimetry and modelling provides a way to hindcast wave data for individual cyclones (Bosserelle, 2015), derived wave data are more representative of offshore conditions rather than wave characteristics experienced directly along affected coastlines. Moreover, such methods cannot be applied to palaeo-cyclones. For this, other methods are needed. One technique available is inverse modelling of wave heights and flow velocities from the characteristics of wave-transported coastal boulders (Nandasena et al., 2011; 2013; Nakamura et al., 2014; Weiss and Diplas, 2015).

1.2 Study aims

The principal aim of this study is to delineate the characteristics of nearshore storm waves generated by Winston on the northern Fiji island of Taveuni (N16°50', 180°). Findings are then compared with the magnitude of storm waves generated by earlier cyclones, both recent and prehistorical. This work is carried out to determine whether Winston was the most powerful storm to have struck Fiji over past decadal to centennial timescales. Such knowledge deduced from comparisons of cyclone-generated extreme wave magnitudes will be a useful guide in future endeavours pertaining to coastal hazard perceptions across Fiji and beyond. The task is accomplished using geomorphic proxy methods to interpret wave characteristics, namely wave heights at breaking and resulting water flow velocities induced at the coastline. Methods are based on the analysis of large reef-derived carbonate boulders that were transported and deposited on Taveuni's eastern coastline during Winston and older extreme events.

Taveuni Island is selected as the study site because it lay adjacent on the north side of Winston's track and was therefore heavily impacted by storm waves. Furthermore, Taveuni's coastal storm deposits have previously been investigated following an earlier cyclone strike by Tomas in 2010 (Fig. 1), for which data are available allowing useful comparison (Etienne and Terry, 2012; Terry and Etienne, 2014). Tomas had a contrasting track to Winston, approaching Taveuni from the north rather than the east. On 15 March 2010, Tomas passed 30 km east of Taveuni (Fig. 1); this track orientation meant that winds of 100 knots (185 km hr^{-1}) and gusts up to 140 knots (259 km hr^{-1}) were directed onshore along the eastern coast of Taveuni as the storm approached. Consequently, heavy swells of 4 m or more offshore were generated (FMS, 2010). Unconfirmed media reports mentioned floods (storm waves and storm surge combined) over 7 m at the coast, causing inundation of low-lying areas by Tomas.

1.3 Coastal boulder investigations

1.3.1 Boulder proxies for storm events

First described in the early 20th Century as a potential proxy for high-magnitude storms (Hedley and Taylor, 1907), coastal boulder analysis is now a well-established field in (palaeo)geomorphological research, and has been applied across a range of tropical and extra-tropical regimes (Etienne and Paris, 2010; Goto et al., 2010; Terry et al., 2013; Lau et al., 2015). Coastal boulder deposits have been used to characterise the nature of palaeo-storms (and tsunamis), enabling comparisons with recent events, and permitting approximations of the temporal frequencies of the strongest events experienced over centennial to millennial timescales on specific coastlines. Measuring the position, orientation and size of coastal boulders reveals clues concerning the characteristics (e.g., height, direction, power) of the storm waves that deposited them (Goto, 2009; Etienne, 2012; May et al., 2015). Tropical coasts behave differently from mid- and high-latitude coasts because the interaction of storm waves with fringing coral reefs produce and transport low-density boulders of carbonate lithology that may be distributed in boulder fields across reef platforms. Carbonate boulders sourced from living reefs fringing a coastline may yield information on the timing of palaeo-cyclone events through the cautious application of laboratory age-dating of boulder coral fabric (Hearty, 1997; Zhao et al., 2009; Yu et al., 2009, 2012; Atwater et al., 2017).

1.3.2 Boulder movement by waves

Understanding the hydrodynamic mechanisms responsible for boulder dislodgement by causative waves, their subsequent movement, and the interaction of physical influences, are complex problems. Boulders normally possess irregular shapes, which interact in a non-linear fashion with the turbulent water flow around them (Weiss and Diplas, 2015). The pre-transport setting, i.e., whether boulders are bounded by, or free of, their parent rock mass (Nott, 2003), rock-platform geomorphic features such as boulder traps and topographic irregularities (Naylor et al., 2016), and bed slope and roughness in the vicinity of boulders (Weiss and Diplas, 2015), are all crucial factors in both initial boulder dislodgement and total wave transport.

A principal pursuit has been to determine whether any boulder evidence can be used to distinguish between storm and tsunami waves (e.g., Nott, 1997; Noormets et al., 2004; Switzer and Burston, 2010; Atwater et al., 2017). One observation has been that the numerous waves impinging on coasts during storms can organise boulders in landward-fining trends (although this is not always the case, e.g., Naylor et al., 2016), whereas more powerful but individual tsunami waves are more likely to leave erratic and disorganised boulder distributions (e.g., Goto et al., 2010; Weiss, 2012). However, recent work is challenging earlier ideas that storm-driven waves are less competent than tsunamis at large boulder transport. Detailed investigation of coastal conditions during 2013 Supertyphoon Haiyan in The Philippines, through wave modelling and observations caught on film, combined with examination of resulting coastal deposits, has shown that surf beat and long-period infragravity waves can produce tsunami-like bores, capable of quarrying and redistributing very large clasts and lifting boulders to elevations up to 10 m (May et al., 2015; Roeber and Bricker, 2015). In consequence, Kennedy et al. (2017) reach the conclusion that the largest blocks transported by storm waves overlap much of the tsunami transport range.

2. Tropical Cyclone Winston, February 2016

2.1 Cyclone track and characteristics

RSMC-Nadi[1] in Fiji, operated by the Fiji Meteorological Service (FMS), is the authority designated by the WMO to monitor cyclone development in the South Pacific, within the area 0°–25°S and 160°E–120°W. The South Pacific cyclone season typically spans six months from November to April. Terry (2007) provides a list of tropical cyclones in the South Pacific over almost four decades from 1969 (n = 291), revealing a mean frequency of nine cyclones per season for the basin, with February being

[1] Regional Specialized Meteorological Centre

statistically the most active month. The 2015-2016 cyclone season commenced during an El Niño phase of ENSO. Warm sea surface temperature anomalies prevailed across nearly the entire equatorial Pacific in December 2015, such that conditions in January 2016 remained indicative of a strong El Niño (FMS, 2016a). El Niño periods tend to spread cyclogenesis eastwards in the South Pacific (Basher and Zheng, 1995; Chu, 2004; Terry and Etienne, 2010). Cyclonic activity was therefore centred on the mid-region of the basin in the early part of 2016.

Winston was the fourth system of the 2015-2016 South Pacific cyclone season. The system began as tropical disturbance no. TD09F and was monitored from 7 February onwards by RSMC-Nadi while developing to the northeast of Vanuatu (Fig. 1). Aided by conducive atmospheric conditions, the system initially tracked towards the southeast with deepening convection and resulting intensification (FMS, 2016b). On 11 February the system attainted cyclone strength (sustained winds ≥35 knots) and was named 'Winston'. The system changed course abruptly on 14 February, veering northeast towards Tonga. Decelerating on 18 February, the system became almost stationary whilst located approximately 200 km northwest of Niue island. Influenced by a sub-tropical ridge of high pressure to the south, Winston doubled back on a new westwards track. Over the following two days as it entered Fiji waters from the east, the system underwent renewed acceleration and intensification to a category-5 system on the Australian Tropical Cyclone Intensity Scale (BoM, 2017). On 20 February, Winston made landfall on Vanuabalavu in eastern Fiji's Lau group of islands. At 06:00 local time on 20 February, the FMS weather centre on Vanuabalavu recorded gusts of 160 knots (305 km hr^{-1}) before the anemometer was destroyed. Around midday Winston's track crossed the southern tip of Taveuni island (Fig. 2); shortly thereafter the storm acquired peak intensity as its central pressure fell to 884 hPa with 10-minute maximum sustained winds reaching 150 knots (280 km hr^{-1}) (APDRC, 2017). Later the same day, the storm made landfall again on the northeast mainland coast of Viti Levu island, and followed a westward path until it vacated Fiji waters on 21 February.

2.2 Coastal floods

Strong winds were largely responsible for Winston's scale of destruction across Fiji; but on exposed island coastlines facing the storm's approach, marine inundation driven by powerful storm waves contributed as a major cause of damage (Fig. 2). Over two thirds of lives lost were claimed by flooding of low-lying coastal communities (WMO, 2016). Modest storm surge 0.5 m above predicted sea level on 20 February was modelled for Levuka on Ovalau island which lay 35 km to the south of the cyclone track, 135 km southwest of Taveuni (GDACS, 2017). However, wind-driven wave set-up added significantly to the storm surge. Hindcast offshore maximum wave heights (H_s) were between 5–10 m for Taveuni island and 10–>12 m for Koro island (SPC, 2016). The media reported eyewitness accounts of waves 12 m in height. Shoreline inundation levels of over 3 m were indicated by the removal of bark on coconut trees at Muamua village on Vanuabalavu island (Needham, 2016), and 2 m from damage to houses observed by the authors on the northeast coast of Viti Levu Island. On the Lavena peninsula on Taveuni island, sea flooding driven by storm waves also penetrated inland. Residents inhabiting houses closest to the shore evacuated when seawater reached waist height (approximately 1 m) and moved to safety to houses farther inland on higher ground.

3. Methods

3.1 Study area and measurements

In eastern Taveuni between 8 and 11 June 2016, approximately three months after the cyclone, we inspected Winston's impact at Lavena (S16°52.5' W179°53') and Bouma (S16°49.5' W179°52') villages (Fig. 3). These specific study sites were selected because similar field investigations had been carried out in 2010 in the wake of Tomas, another severe tropical cyclone that had affected the Fiji Islands (Etienne and Terry, 2012). Pre-Winston data are thus available for comparison with new observations. Also important were the close ties built up on previous occasions with the villages on Taveuni, which enabled permission to be sought to carry out fieldwork at a sensitive time when the community was still in an early stage of recovery from the Winston disaster.

Storm boulders cast up onto reef flats (Fig. 4) were examined in order to inversely model the nearshore characteristics of the storm waves responsible. In the field, all new boulders produced by Winston waves were mapped using a handheld GPS (Garmin Etrex 10) and measured by tape along their three axes for estimating volume and mass. Distance between a boulder and its inferred boulder source at the nearest reef edge was measured using a laser range-finder. Newly-produced Winston boulders were easily spotted because coral structures appeared fresh and uneroded, and/or erosion surfaces and scars were exposed along boulder faces that had broken away from the reef framework (Fig. 4). In addition, the youngest, recently-living coral skeletons in new reef clasts were typically overgrown by green algae, owing to their mortality caused by being removed from the marine environment during the cyclone. The covering of marine algae gave fresh boulders a distinctive greenish tinge, which stood out clearly from the grey colour of neighbouring older boulders on the reef platform. Identification of newly-deposited boulders was also verified by local people based on their memory of pre-Winston conditions, and by comparing with boulder positions that were mapped in earlier investigations.

Pre-Winston boulder data had been previously collected in July 2010, four months after the occurrence of Tomas in Fiji. Of all earlier boulder data presented in the work of Etienne and Terry (2012), only larger clasts with long-axes over 1 m are included in the current analysis, as the objective here is to focus on comparing extreme wave events representing past cyclones with the

Winston event. Uranium-thorium ages of older boulders were included from the published data of Terry and Etienne (2014). Boulders investigated on Taveuni were thus organised into three groups, according to depositional timing (from youngest to oldest) during: (1) Winston in 2016, (2) Tomas in 2010, and (3) earlier storms prior to 2010.

As coral boulders are highly irregular and often non-rectangular in shape, boulder sizes were calculated as ellipsoid volumes to avoid overestimation:

$$V = \frac{4}{3} \cdot \pi \cdot \frac{a}{2} \cdot \frac{b}{2} \cdot \frac{c}{2} \qquad (1)$$

where V represents boulder volume; a, b, c are lengths of the long, intermediate, and short axes, respectively.

Boulder mass was subsequently estimated by multiplying volume and boulder density, the latter determined as 1.8 t m^{-3} from samples measured in the laboratory (see Lau et al., 2016).

3.2 Calculation of wave characteristics

Extreme wave characteristics were back-calculated, i.e., inversely modelled, by applying a variety of published numerical equations based on boulder dimensions and masses. Flow velocity, wave height and energy of waves at the reef crest were estimated as the minimum values required to initiate boulder transport.

3.2.1 Minimum flow velocity

Flow velocity was calculated using a hydrodynamic equation developed by Nandasena et al. (2011). The equation yields the minimum flow velocity required to initiate each boulder's vertical movement by a lift force from the reef edge onto the reef flat:

$$u^2 \geq \frac{2(\rho_s / \rho_w - 1) g c \cos\theta}{C_l} \qquad (2)$$

where u is flow velocity (m s^{-1}); c is the boulder short axis length (m); ρ_s is boulder density; ρ_w is water density (1.025 g ml^{-1}); Cl is the lift coefficient (0.178); θ is the angle of the bed slope at pre-transport location (1° at this site); and g is the acceleration of gravity (9.81 m s^{-2}).

For the remobilisation by storm waves of pre-existing boulders that were already present on the reef flat, the required flow velocity is lower because boulder movement can be initiated by sliding or rolling, rather than lifting as described by equation (2). Minimum flow velocity for remobilising boulders by sliding and rolling respectively is calculated from equations (3) and (4) (Nandasena et al., 2011):

$$u^2 \geq \frac{2(\rho_s / \rho_w - 1) g c (\mu \cos\theta + \sin\theta)}{C_d (c / b) + \mu\, C_l} \qquad (3)$$

$$u^2 \geq \frac{2(\rho_s / \rho_w - 1) g c (\cos\theta + (c / b) \sin\theta)}{C_d (c^2 / b^2) + C_l} \qquad (4)$$

<u>3.2.2 Minimum wave height</u>

Storm wave height was estimated as the minimum wave height that was required to dislodge and lift each bounder using a published equation from the work of Engel and May (2012):

$$Hs = \frac{(\rho_s - \rho_w)V(cos\theta + \mu\ sin\theta)}{0.5\ \rho_w C_l\ a\ b} \quad (5)$$

where *Hs* is storm minimum wave height (m); *V* is volume (m^3); μ is the coefficient of static friction (0.7 on reef); *a* and *b* are the boulder long and intermediate axial lengths, respectively (m).

3.2.3 Minimum kinetic energy

The minimum kinetic energy equired for a wave to lift a boulder onto the reef was calculated as the potential energy (*PE*) of the displaced boulder at its present height:

$$PE = mgh \quad (6)$$

where *m* is boulder mass (kg); and *h* is the height of displacement (m), which is at least equivalent to, if not greater than, the boulder short-axis length (Fig. 5).

4. Results

4.1 Boulder characteristics

Storm waves during Winston deposited 13 large carbonate boulders with b-axis ≥1 m on the coastal reef platforms near Lavena village on Taveuni (Fig. 5), as well as numerous smaller coral clasts.

Corals in the boulder framework showed signs of recent mortality, revealing that these boulders had been quarried from the adjacent living reef front, rather than older non-living reef framework at depth. One individual boulder with dimensions of 7.2 × 3.9 × 2.3 m (33.8 m^3, 60.9 t in mass; Fig. 4a) is notable as the biggest wave-lifted clast observed to date on Taveuni and elsewhere in the Fiji Islands (Fig. 6).

The 3D shape (form) of our measured boulders is seen to fall within various categories according to the classification system of Blott and Pye (2008), although the majority of Winston boulders are blocky in shape, and are therefore similar to boulders deposited by earlier cyclones (Fig. 7). It is interesting to note that all new Winston boulders were deposited on the south-facing coast to the west of Lavena village. This contrasts with boulders deposited by Tomas storm waves in 2010 (n=18, up to 6.3 m^3 and 11.3 t), which were mostly mapped on east-facing reefs near Bouma village. An additional 111 older boulders emplaced by earlier cyclones are also included in our analysis. These boulders are found at multiple locations, with the largest individual (21.3 m^3, 38.3 t) observed near Matakuro settlement (Fig. 5).

4.2 Inferred wave conditions

The depositional configuration of Winston boulders is restricted to the coast to the west of Lavena village, indicating that the strongest storm waves during the cyclone approached Taveuni from southerly or southwesterly directions. At the point of breaking over the reef edge, the strongest waves reached a minimum wave height of at least 10 m, generated minimum flow velocity over 13.8 $m\ s^{-1}$, and produced a minimum kinetic energy of 1.4×10^6 J. These minimum values are inferred from the forces required to lift the largest observed boulder 60.9 t in mass onto the reef platform. Thereafter, these storm waves lost some energy as they propagated across the reef flat, dropping the largest boulder from entrainment approximately 30 m from the reef edge. Wave dissipation was presumably enhanced by the relatively low level of the storm tide on the reef, owing to the timing of Winston's approach towards Taveuni an estimated one hour before low tide. It might be assumed that wave power across the fringing reefs, boulder transport capabilities, and the likely resulting coastal damage, would have all been far greater had Winston's traversal of southern Taveuni coincided with high tide. Nonetheless, marine flooding driven by storm waves managed to penetrate inland onto the Lavena peninsula during Winston. Residents of Lavena occupying houses nearest the shore evacuated when seawater reached waist height and moved to safety to houses on higher ground. A sand sheet was deposited on the south side of the peninsula up to 30–40 m inland of the shoreline vegetation, as seen in Fig. 2, although this was not sampled or examined in detail.

On the east-facing reefs near Bouma, although no new large boulders (b-axis ≥ 1 m) were produced by Winston storm waves, the largest boulder emplaced by Tomas in 2010 (with a mass of 8.8 t) was found to have been remobilised by Winston waves and pushed more than 20 m landwards in a transport direction from southeast to northwest. Taking the conservative approach that this boulder was transported by sliding (rather than rolling or saltation), results indicate a minimum flow velocity of at least 3.75 m s^{-1} was generated over the Bouma reef flat.

5. Discussion

5.1 Comparisons with earlier Fiji cyclones

The contrasting reef boulder distributions in eastern Taveuni produced by Winston in 2016 and Tomas in 2010 can best be explained by the different orientations of the tracks of these two cyclones (Fig. 1), even though both storms passed similarly close to the study sites. The influence of the Lavena peninsula (Fig. 3) would have been important, providing relative shelter from storm waves for the shoreline immediately to the south of the peninsula during the approach of Tomas and to the north of the peninsula during Winston. Similarly, our estimations of wave characteristics (Fig. 8), based on transported boulder measurements, suggest that the magnitudes of storm waves produced by Winston were somewhat lower than those produced by Tomas on east-facing reefs (e.g., near Bouma), but were greater on south-facing reefs west of Lavena, mainly owing to the contrasting track orientations of these storms, as mentioned above. Support is given by the stochastic cyclone simulations of Hoeke et al. (2015) for the Samoan capital of Apia on the island of Upolu. They note that factors besides cyclone proximity and wind strength are important influences on maximum wave energy flux, including cyclone track orientation, radius of strongest winds and propagation speed; and that resulting levels of water incursion at local scales (<1 km) are sensitive to local (coastal) morphology.

Winston in 2016 ranks as the most powerful cyclone on record in Fiji, as well as being the strongest cyclone to make landfall in the South Pacific islands since instrumented monitoring began. In spite of this, however, the geological evidence of pre-existing carbonate boulder deposits on reef platforms fringing the coastline of eastern Taveuni implies that numerous extreme wave events have occurred in both recent historical and prehistorical times. Previous age-dating of coastal carbonate boulders on Taveuni (Fig. 8) has revealed that at least seven events, presumably cyclone-driven, have occurred since 1650 CE (Terry and Etienne, 2014). Moreover, wave magnitudes during several prehistorical events were comparable to, if not exceeded, conditions generated by Winston. Particularly notable is boulder evidence of three distinct extreme wave events characterised by minimum wave heights over 8 m high and minimum flow velocities greater than 12 m s^{-1}. The implication is that the extreme wave magnitudes generated by Winston, and by inference the intensity of the cyclone itself, although devastating by modern standards, are not unique if viewed across centennial timescales.

Additionally, old storm boulders have been worn down by marine abrasion and weathering over longer periods than more recent deposits and are smaller now than when originally deposited. The amount of size (volume and mass) reduction is, however, unknown. This means that inverse modelling from boulder deposits likely underestimates the magnitude of wave characteristics during palaeo-cyclone events and cannot account for dissipation over complex coral flats. To tackle the problem of underestimation, we suggest that further work is required, including laboratory and field experiments, in order to develop a suitable model for boulder size reduction over time, which can be applied to hindcast approximate original boulder size at the time of deposition. Such a model is likely to be non-linear. This is because carbonate boulder size reduction will accelerate over time, especially once boulders become small enough to be transported by annual maximum storm waves.

5.2 Brief comparisons with Typhoon Haiyan

Winston in the South Pacific can be compared with the case of Supertyphoon Haiyan in the North West Pacific, which devastated Leyte and Samar islands in the Eastern Visayas region of the eastern Philippines in November 2013. Haiyan's coastal impacts have recently been the subject of concerted research investigation (Bricker et al., 2014; May et al., 2015; Soria et al., 2016; Kennedy et al., 2017). In terms of storm intensity, Winston surpassed Haiyan, attaining a minimum pressure of 884 hPa compared to 895 hPa, and maximum 10-minute sustained wind speeds of 280 km hr^{-1} compared to 230 km hr^{-1}. The largest new reef-platform clast emplaced by Winston in Taveuni (7.2 × 3.9 × 2.3 m) compares well with the largest carbonate clasts (7.3 × 5.1 × 3.2 m and 5.3 × 3.0 × 2.9 m) observed to have been transported by lifting or saltation during Typhoon Haiyan in Eastern Samar, as reported by May et al. (2015) and Kennedy et al. (2017). Initially, this might suggest that similar wave conditions and coastal inundation were experienced in Fiji and The Philippines. However, several contrasts exist. During Haiyan, in the shallow embayment of the northern Leyte Gulf (N11°7' E125°7'), extreme marine inundation was mainly the result of the wind-setup component of the storm surge (Bricker et al., 2014; Soria et al., 2016) amplified by seiche (Mori et al., 2014). The storm surge reached 2 km inland at Tacloban City, with surge water trapped by bordering high mountains (Lagmay et al., 2015). Elsewhere, on the more exposed open-sea coast of the Hernani area (N11°18' E125°36'), wave breaking set-up across the fringing reef and infragravity waves resulting from surf beat (May et al., 2015; Roeber and Bricker, 2015) produced a powerful tsunami-like bore.

Both these inundation situations (seiche and infragravity waves) during Typhoon Haiyan contrast with the experience at Lavena on Taveuni Island in Fiji during Winston. There, wave-driven flood waters from the south would have been able to sweep across the low-lying Lavena peninsula, without building up to significant depths. The lack of a deep embayment in the coastal configuration also avoided water funnelling or seiche effects. Furthermore, there were no eyewitness accounts of tsunami-like bores during Winston. These observed differences in coastal effects between extreme storms Winton and Typhoon Haiyan underscore the importance of understanding the local influences of coastal morphology, to allow interpretation of the causes of marine inundation and the type of sediment transport processes operating.

5.3 Further perspectives

For Taveuni island in north eastern Fiji, normally exposed to cyclones that approach from the north, it should be noted that the most powerful storms in recent years (Raja 1986, Tomas 2010, Winston 2016) all arrived during low tide. It is important to bear in mind that some previous studies emphasise a nonlinear interaction between storm surges and tides (Tang et al., 1996; Rego and Li, 2010), such that the greatest storm surge height is not necessarily produced at highest tide.

Nonetheless, marine flooding might have been greater if these cyclones had coincided with high tide.

We are reminded by the WMO (2016) that better strategies to reduce vulnerability to natural disasters are needed to achieve improved sustainability and resilience in the Pacific Islands. Because the majority of Pacific Islands' populations inhabits coastal areas, livelihoods, communities and national economies are especially susceptible to threats posed by extreme weather perils. The continuing vulnerability of coastal communities will therefore need careful assessment as a basis for sound socio-economic and environmental planning activities at both local and national scales. Greater resilience can be built if local authorities have more detailed knowledge of cyclone-driven conditions that might be expected in future. The Fiji population as a whole would benefit from being made aware that Winston, although the strongest landfalling cyclone on record in the South Pacific Islands, has been matched by several events of similar or greater magnitude on past centennial timescales.

From a scientific perspective, further research to reconstruct prehistorical cyclones would be worthwhile, both in Fiji and across neighbouring island archipelagos in the South Pacific. Such work has commenced for example in French Polynesia (Lau et al., 2014; 2016). Through regional comparisons, a clearer picture should eventually begin to emerge on whether past phases of extreme event occurrence can be identified, and whether or not these show any association with distinct climatic periods, such as the Little Ice Age as experienced in the Pacific Basin or the apparently pivotal period referred to as the 'AD 1300 Event' (Nunn 2007, Nunn and Hunter-Anderson, 2011). Palaeo-cyclone reconstruction would also provide a yardstick against which to assess our current capabilities at cyclone prediction and modelling, and may support other efforts focused on deciphering modern cyclogenesis patterns in the South Pacific (e.g., Magee et al., 2017; Diamond et al., 2015a; 2015b).

5. Conclusions

We present the first study on the magnitude of the coastal waves generated by Cyclone Winston when it struck Fiji in February 2016. Large reef-derived coral boulders quarried and emplaced on the east coast of Taveuni island indicate that maximum breaking waves were at least 10 m high and generated flow velocities in excess of 13.8 m s^{-1}. Waves delivered sufficient energy to dislodge and lift boulders up to 34 m^3 in size and weighing 61 t. Nevertheless, we also conclude that despite being the strongest cyclone to impact Fiji since instrumented records began, the nearshore conditions experienced during Winston are not unprecedented. The assemblage of older carbonate boulder fields provides evidence that Taveuni's coastlines have been struck over the past 400 years by at least seven extreme events comparable to or stronger than Winston. In terms of anticipating worst-case coastal hazard scenarios for Fiji, the prospect of cyclone arrival being coincident with high tide is an additional consideration. Detailed storm surge and wave modelling is therefore needed to investigate possible marine incursion by a future Winston-type event under such conditions.

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References

APDRC, 2017. Asia-Pacific Data-Research Center. Southwest Pacific Enhanced Archive for Tropical Cyclones (SPEArTC), accessed August 2017, http://apdrc.soest.hawaii.edu/projects/speartc/.

Atwater, B.F., ten Brink, U.S., Cescon, A.L., Feuillet, N., Fuentes, Z., Halley, R.B., Nuñes, C., Reinhardt, E.G., Roger, J.H., Sawai, Y., Spiske, M., Tuttle, M.P., Wei, Y., Weil-Accardo, J., 2017. Extreme waves in the British Virgin Islands during the last centuries before 1500 CE. Geosphere 13, 301-368.

Basher, R.E., Zheng, X., 1995. Tropical cyclones in the southwest Pacific: spatial patterns and relationships to Southern Oscillation and sea surface temperature. Journal of Climate 8, 1249-1260.

Blott, S.J., Pye, K., 2008. Particle shape: A review and new methods of characterization and classification. Sedimentology 55, 31-63.

BoM, 2017. Tropical Cyclone Intensity and Impacts. Australian Bureau of Meteorology, accessed January 2017, http://www.bom.gov.au/cyclone/about/intensity.shtml#WindC.

Bosserelle, C., 2015. Tropical Cyclone Pam waves summary. Secretariat of the Pacific Community (SPC), Noumea, New Caledonia, 9 pp. accessed January 2017, https://pcrafi.spc.int/static/pam/TropicalCyclonePamSwellSummary.pdf.

Bricker, J.D., Takagi, H., Mas, E., Kure, S., Adriano, B., Yi, C., Roeber V., 2014. Spatial variation of damage due to storm surge and waves during Typhoon Haiyan in the Philippines. Journal of Japan Society of Civil Engineers Series B2 (Coastal Engineering) 70, 231-235.

Chu, P-S., 2004. ENSO and tropical cyclone activity. In: Murnane, R.J., Liu, K.-B. (Eds.), Hurricanes and Typhoons: Past, Present and Future. Columbia University Press, New York, pp. 297-332.

Cruz-Castro, O., 2016. Review of coastal modeling using HPC and ADCIRC+SWAN to predict storm surge, waves and winds, produced by a hurricane. In: Gitler I., Klapp J. (Eds.), High Performance Computer Applications. Communications in Computer and Information Science. Springer, Cham, 595, pp. 523-534.

Diamond, H.J., Lorrey, A.M., Renwick, J.A., 2013. A southwest Pacific tropical cyclone climatology and linkages to the El Niño–Southern Oscillation. Journal of Climate 26, 3-25.

Diamond, H.J., Renwick, J.A., 2015a. The climatological relationship between tropical cyclones in the southwest Pacific and the southern annular mode. International Journal of Climatology 35, 613-623.

Diamond, H.J., Renwick, J.A., 2015b. The climatological relationship between tropical cyclones in the southwest pacific and the Madden–Julian Oscillation. International Journal of Climatology 35, 676-686.

Dowdy, A., Qi, L., Jones, D., Ramsay, H., Fawcett, R., Kuleshov, Y., 2012. Tropical cyclone climatology of the South Pacific Ocean and its relationship to El Niño–Southern Oscillation. Journal of Climate 25, 6108-6122.

Engel, M., May, S.M., 2012. Bonaire's boulder fields revisited: evidence for Holocene tsunami impact on the Leeward Antilles. Quaternary Science Reviews 54, 126-141.

Etienne, S., 2012. Marine inundation hazards in French Polynesia: geomorphic impacts of Tropical Cyclone Oli in February 2010. In: Terry, J.P., Goff, J. (Eds.), Natural hazards in the Asia–Pacific Region: Recent Advances and Emerging Concepts. Geological Society of London, Special Publication 361, pp. 21-39.

Etienne, S., Paris, R., 2010. Boulder accumulations related to storms on the south coast of the Reykjanes Peninsula (Iceland). Geomorphology 114, 55-70.

Etienne, S., Terry, J.P., 2012. Coral boulders, gravel tongues and sand sheets: features of coastal accretion and sediment nourishment by Cyclone Tomas (March 2010) on Taveuni Island, Fiji. Geomorphology 175-176, 54-65.

FMS, 2016a. Fiji Meteorological Service. ENSO Update 9, 4 pp.

FMS, 2016b. Fiji Meteorological Service. Preliminary Report on Severe Tropical Cyclone Winston (Cat5), 9 pp.

FMS, 2016c. Fiji Meteorological Service. Fiji Climate Summary February 2016 37, 11 pp.

GDACS, 2017. Storm surge for tropical cyclone WINSTON-16. Global Disaster Alert and Coordination System, United Nations and European Commission. Accessed June 2017, http://www.gdacs.org/Cyclones/stormsurge.aspx?eventid=1000252&episodeid=22&eventtype=TC.

Goto, K., Okada, K., Imamura, F., 2009. Characteristics and hydrodynamics of boulders transported by storm waves at Kudaka Island, Japan. Marine Geology 262, 14-24.

Goto, K., Shinozaki, T., Minoura, K., Okada, K., Sugawara, D., Imamura, F., 2010. Distribution of boulders at Miyara Bay of Ishigaki Island, Japan: a flow characteristic indicator of tsunami and storm waves. Island Arc 19, 412-426.

Hearty, P., 1997. Boulder deposits from large waves during the Last Interglaciation on North Eleuthera Island, Bahamas. Quaternary Research 48, 326-338.

Hedley, C., Taylor, T.G., 1907. Coral reefs of the Great Barrier, Queensland: a study of their structure, life-distribution and relation to mainland physiography. Australasian Association for the Advancement of Science 11, 397-413.

Hoeke, R.K., McInnes, K.L., O'Grady, J.G., 2015. Wind and wave setup contributions to extreme sea levels at a tropical high island: a stochastic cyclone simulation study for Apia, Samoa. Journal of Marine Science and Engineering 3, 1117-1135.

Kennedy, A.B., Mori, N., Yasuda, T., Shimozono, T., Tomiczek, T., Donahue, A., Shimura, T., Imai, Y., 2017. Extreme block and boulder transport along a cliffed coastline (Calicoan Island, Philippines) during Super Typhoon Haiyan. Marine Geology 383, 65-77.

Kuleshov, Y., Qi, L., Fawcett, R., Jones, D., 2008. On tropical cyclone activity in the Southern Hemisphere: trends and the ENSO connection. Geophysical Research Letters 35, L14S08, doi:10.1029/2007GL032983.

Lagmay, A.M.F., Agaton, R.P., Bahala, M.A.C., Briones, J.B.L.T., Cabacaba, K.M.C., Caro, C.V.C., Dasallas, L.L., Gonzalo, L.A.L., Ladeiro, C.N., Lapidez, J.P., Mungcal, M.T.F., Puno, J.V.R., Ramos, M.M.A.C., Santiago, J., Suarez, J.K., Tablazon, J.P., 2015. Devastating storm surges of Typhoon Haiyan. International Journal of Disaster Risk Reduction 11, 1-12.

Lau, A.Y.A., Etienne, S., Terry, J.P., Switzer, A.D., Lee, Y.S., 2014. A preliminary study of the distribution, sizes and orientations of large reef-top coral boulders deposited by extreme waves at Makemo Atoll, French Polynesia. Journal of Coastal Research, Special Issue 70, 272-277.

Lau, A.Y.A., Terry, J.P., Switzer, A., Pyle, J., 2015. Advantages of beachrock slabs for interpreting high-energy wave transport: evidence from Ludao Island in southeastern Taiwan. Geomorphology 228, 263-274.

Lau, A.Y.A., Terry, J.P., Ziegler, A.D., Switzer, A.D., Lee, Y., Etienne, S., 2016. Understanding the history of extreme wave events in the Tuamotu Archipelago of French Polynesia from large carbonate boulders on Makemo Atoll, with implications for future threats in the central South Pacific. Marine Geology 380, 174-190.

Magee, A.D., Verdon-Kidd, D.C., Kiem, A.S., Royle, S.A., 2016. Tropical cyclone perceptions, impacts and adaptation in the Southwest Pacific: an urban perspective from Fiji, Vanuatu and Tonga. Natural Hazards and Earth System Sciences 16, 1091-1105.

Magee, A.D., Verdon-Kidd, D.C., Diamond, H.J., Kiem, A.S. 2017. Influence of ENSO, ENSO Modoki, and the IPO on tropical cyclogenesis: a spatial analysis of the southwest Pacific region. International Journal of Climatology 37, 1118–1137.

May, S.M., Engel, M., Brill, D., Cuadra, C., Lagmay, A.M.F., Santiago, J., Suarez, J.K., Reyes, M., Brückner, H., 2015. Block and boulder transport in Eastern Samar (Philippines) during Supertyphoon Haiyan. Earth Surface Dynamics 3, 543-558.

Mori, N., Kato, M., Kim, S., Mase, H., Shibutani, Y., Takemi, T., Tsuboki, K., Yasuda, T., 2014. Local amplification of storm surge by Super Typhoon Haiyan in Leyte Gulf. Geophysical Research Letters 41, 5106-5113.

Nakamura, M., Arashiro. Y., Shiga, S. 2014. Numerical simulations to account for boulder movements on Lanyu Island, Taiwan: tsunami or storm? Earth Planets and Space 66, 128.

Nandasena, N.A.K., Paris, R., Tanaka, N., 2011. Reassessment of hydrodynamic equations to initiate boulder transport by high energy events (storms, tsunamis). Marine Geology 281, 70-84.

Naylor, L.A., Stephenson, W.J., Smith, H., Way, O., Mendelssohn, J., Cowley, A., 2016. Geomorphological control on boulder transport and coastal erosion before, during and after an extreme extra-tropical cyclone. Earth Surface Processes and Landforms 41, 685-700.

Nandasena, N.A.K., Tanaka, N., Sasaki, Y., Osada, M. 2013. Boulder transport by the 2011 Great East Japan tsunami: comprehensive field observations and whither model predictions? Marine Geology 346, 292-309.

Needham, H., 2016. Tree Photos Provide Evidence of a 10-ft (3 m) Storm Surge in Fiji. 22 February 2016, accessed June 2017, http://hurricanehalssb.blogspot.sg/2016/02/tree-photos-provide-evidence-of-10-ft-3.html.

Noormets, R., Crook, K.A., Felton, E.A., 2004. Sedimentology of rocky shorelines: 3.: hydrodynamics of megaclast emplacement and transport on a shore platform, Oahu, Hawaii. Sedimentary Geology 172, 41-65.

Nott, J., 1997. Extremely high-energy wave deposits inside the Great Barrier Reef, Australia: determining the cause—tsunami or tropical cyclone. Marine Geology 141, 193-207.

Nott, J., 2003. Waves, coastal boulder deposits and the importance of the pre-transport setting. Earth and Planetary Science Letters 210, 269-276.

Nunn, P.D. 2007. The A.D. 1300 Event in the Pacific Basin. The Geographical Review 97, 1-23.

Nunn, P.D. and Hunter-Anderson, R. 2011. Defending the Defensible: A rebuttal of Scott Fitzpatrick's (2010) critique of the AD 1300 Event model with particular reference to Palau. Journal of Pacific Archaeology 2, 92-99.

Rego, J.L., Li. C., 2010. Nonlinear terms in storm surge predictions: Effect of tide and shelf geometry with case study from Hurricane Rita. Journal of Geophysical Research 115, C06020, doi:10.1029/2009JC005285.

Roeber, V., Bricker, J., 2015. Destructive tsunami-like wave generated by surf beat over a coral reef during Typhoon Haiyan. Nature Communications 6, 7854, doi:10.1038/ncomms8854.

Soria, J.L.A., Switzer, A.D., Villanoy, C.L., Fritz, H.M., Bilgera, P.H.T., Cabrera, O.C., Siringan, F.P., Yacat-Sta. Maria, Y., Ramos, R.D., Fernandez, I.Q., 2016. Repeat storm surge disasters of Typhoon Haiyan and its 1897 predecessor in the Philippines. Bulletin of the American Meteorological Society 97, 31-48.

SPC, 2016. Fiji: Hindcast Wave Heights for Tropical Cyclone Winston (26 Feb 2016). Secretariat of the Pacific Community, Geosciences Division, Suva, Fiji. Accessed June 2017, https://reliefweb.int/map/fiji/fiji-hindcast-wave-heights-tropical-cyclone-winston-26-feb-2016.

Switzer, A.D., Burston, J.M., 2010. Competing mechanisms for boulder deposition on the southeast Australian coast. Geomorphology 114, 42-54.

Tang, Y.M., Sanderson, B., Holland, G., Grimshaw, R., 1996. A numerical study of storm surges and tides, with application to the north Queensland coast. Journal of Physical Oceanography 26, 2700-2711.

Terry, J.P., 2007. Tropical Cyclones: Climatology and Impacts in the South Pacific. Springer, New York.

Terry, J.P., Etienne, S., 2010. Recent heightened tropical cyclone activity east of 180° in the South Pacific. Weather 65, 193-195.

Terry, J.P., Etienne, S., 2014. Potential for timing high-energy marine inundation events in the recent geological past through age-dating of reef boulders in Fiji. Geoscience Letters 1, 14, doi:10.1186/s40562-014-0014-8.

Terry J.P., Gienko, G., 2010. Climatological aspects of South Pacific tropical cyclones, based on analysis of the RSMC-Nadi (Fiji) regional archive. Climate Research 42, 223-233.

Terry, J.P., Jankaew, K., Dunne, K., 2015. Coastal vulnerability to typhoon inundation in the Bay of Bangkok, Thailand? Evidence from carbonate boulder deposits on Ko Larn Island. Estuarine, Coastal and Shelf Science 165, 261-269.

Terry, J.P., Lau, A.Y., Etienne, S., 2013. Reef-platform Coral Boulders: Evidence for High-energy Marine Inundation Events on Tropical Coastlines. Springer, New York, 210 pp.

UNISDR, 2015. Sendai Framework for Disaster Risk Reduction 2015 – 2030. United Nations Strategy for Disaster Reduction. UNISDR Geneva, Switzerland. Accessed January 2017, http://www.unisdr.org/files/43291_sendaiframeworkfordrren.pdf.

Weiss, R., 2012. The mystery of boulders moved by tsunamis and storms. Marine Geology 295, 28-33.

Weiss, R., Diplas, P., 2015. Untangling boulder dislodgement in storms and tsunamis: Is it possible with simple theories? Geochemistry, Geophysics, Geosystems 16, 890-898.

WMO, 2016. Report of the Sixteenth Session of the WMO RA V Tropical Cyclone Committee for the South Pacific and South-East Indian Ocean. World Meteorological Organization. Accessed December 2016, https://www.wmo.int/pages/prog/www/tcp/documents/RAV_TCC-16_FinalReport_Approved.pdf.

Yu, K., Zhao, J., Shi, Q., Meng, Q., 2009. Reconstruction of storm/tsunami records over the last 4000 years using transported coral blocks and lagoon sediments in the southern South China Sea. Quaternary International 195, 128-137.

Yu, K., Zhao, J., Roff, G., Lybolt, M., Feng, Y., Clark, T., Li, S., 2012. High-precision U-series ages of transported coral blocks on Heron Reef (southern Great Barrier Reef) and storm activity during the past century. Palaeogeography, Palaeoclimatolology, Palaeoecology 337-338, 26-36.

Zhao, J., Neil, D.T., Feng, Y., Yu, K., Pandolfi, J.M., 2009. High-precision U-series dating of very young cyclone-transported coral reef blocks from Heron and Wistari reefs, southern Great Barrier Reef, Australia. Quaternary International 195, 122-127.

Figure Captions

Figure 1. Track map for cyclones Winston in February 2016 (orange line) and Tomas in March 2010 (blue line), showing positions at 6-hourly intervals. Numbers in the round position markers denote the intensity according to the Australian Tropical Cyclone Intensity Scale, which uses a five-category system based on maximum 10-minute sustained winds. Category 1: 34–47 knots (63–87 km/h), Category 2: 48–63 knots (89–117 km/h), Category 3: 64–85 knots (119–157 km/h), Category 4: 86–107 knots (159–198 km/h), Category 5: ≥108 knots (≥200 km/h). For categories 3–5, a system is classified as a ‘severe tropical cyclone’.

Figure 2. (a) Cloud circulation pattern around Winston at 13:30 local time on 20 February 2016 (13:30 FST or 01:30 UTC), shortly after passing immediately south of Taveuni island. The position of the eye is S17°11’, E179°32’, directly over Koro island. Satellite image courtesy of NASA. Photos show the aftermath of damage to east coast villages on Koro (b) and Taveuni (c). The mauve line shows the approximate 30–40 m landward limit of a sand sheet deposited by storm waves within the coastal vegetation on the southern side of the Lavena peninsula (nearest coast facing viewer). Photo credits: Royal New Zealand Air Force.

Figure 3. Study area location on the eastern coast of Taveuni island, showing the fringing coral reef platforms where carbonate boulders (storm deposits) were examined.

Figure 4. Boulders cast up by storm waves during Winston onto Taveuni island's coastal reef flats. (a) The largest new boulder weighing 60.9 t. Close-up: uneroded, bleached coral skeletons are preserved, with a green algal covering. (b) Overturned corals at the base of a 9.3 t boulder indicate that the clast has rolled over the reef flat. Close-up: Several colonies of soft corals still attached to the original reef surface were squashed as the boulder was overturned by wave transport. (c) A 14.2 t boulder with fresh abrasion scars, as indicated by the white arrows. (d) A 4.1 t boulder quarried by storm waves from the offshore living reef is deposited on its 'side' on the reef platform. The youngest coral that was growing on the reef surface prior to excavation of the boulder appears green due to marine algae colonising the areas of recent mortality on the right face, while non-living reef underneath is exposed on the left face.

Figure 5. Distribution of measured carbonate storm boulders on reef platforms fringing the east-facing and south-facing coasts near the villages of Lavena and Bouma in eastern Taveuni.

Figure 6. Frequency histogram of carbonate boulder sizes deposited by various cyclones on the fringing reefs of eastern Taveuni island. Base image courtesy of Google Earth, August 2008.

Figure 7. Three-dimensional form of carbonate boulders (n = 142) deposited by storm waves during recent known and older unknown tropical cyclones on reef platforms fringing the eastern coast of Taveuni.

Figure 8. Comparisons of wave characteristics generated by Winston (2016), Tomas (2010) and earlier cyclone events. Values are determined from the minimum wave heights, flow velocities and kinetic energy requirements needed to lift measured carbonate bounders onto the fringing reef platform from their presumed reef-edge sources. The approximate timing of seven older events

between 1670 CE and 1988 CE is estimated from age-dating using uranium-thorium (U-Th) methods of the youngest coral fabric in individual boulders. Age-dates from Terry and Etienne (2014).

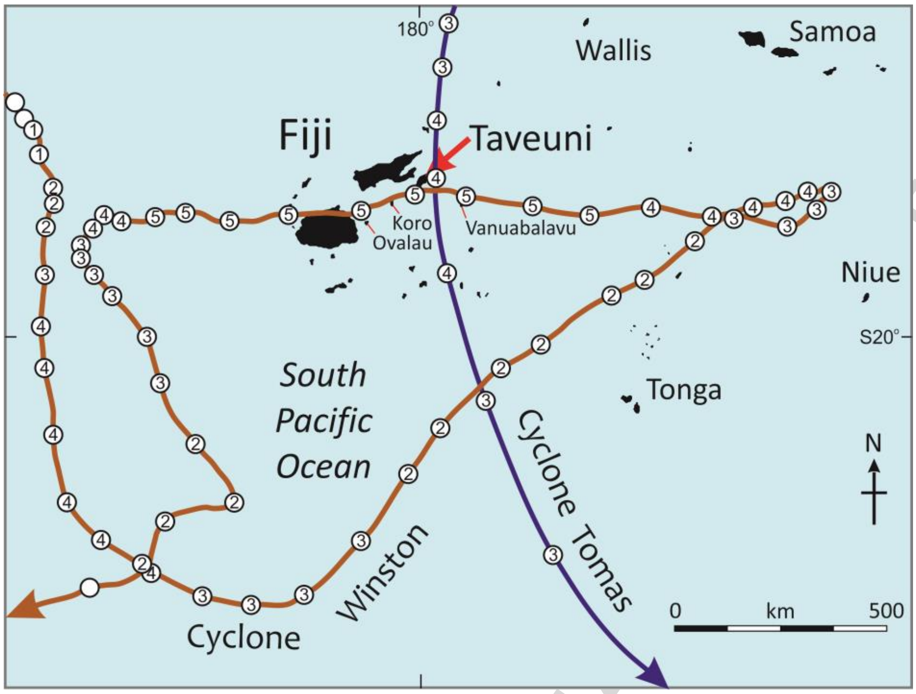

180°
Wallis
Samoa
Fiji
Taveuni
Koro
Ovalau
Vanuabalavu
Niue
S20°
South
Pacific
Ocean
Tonga
N
Cyclone Tomas
Winston
Cyclone
0 km 500

Figure 1

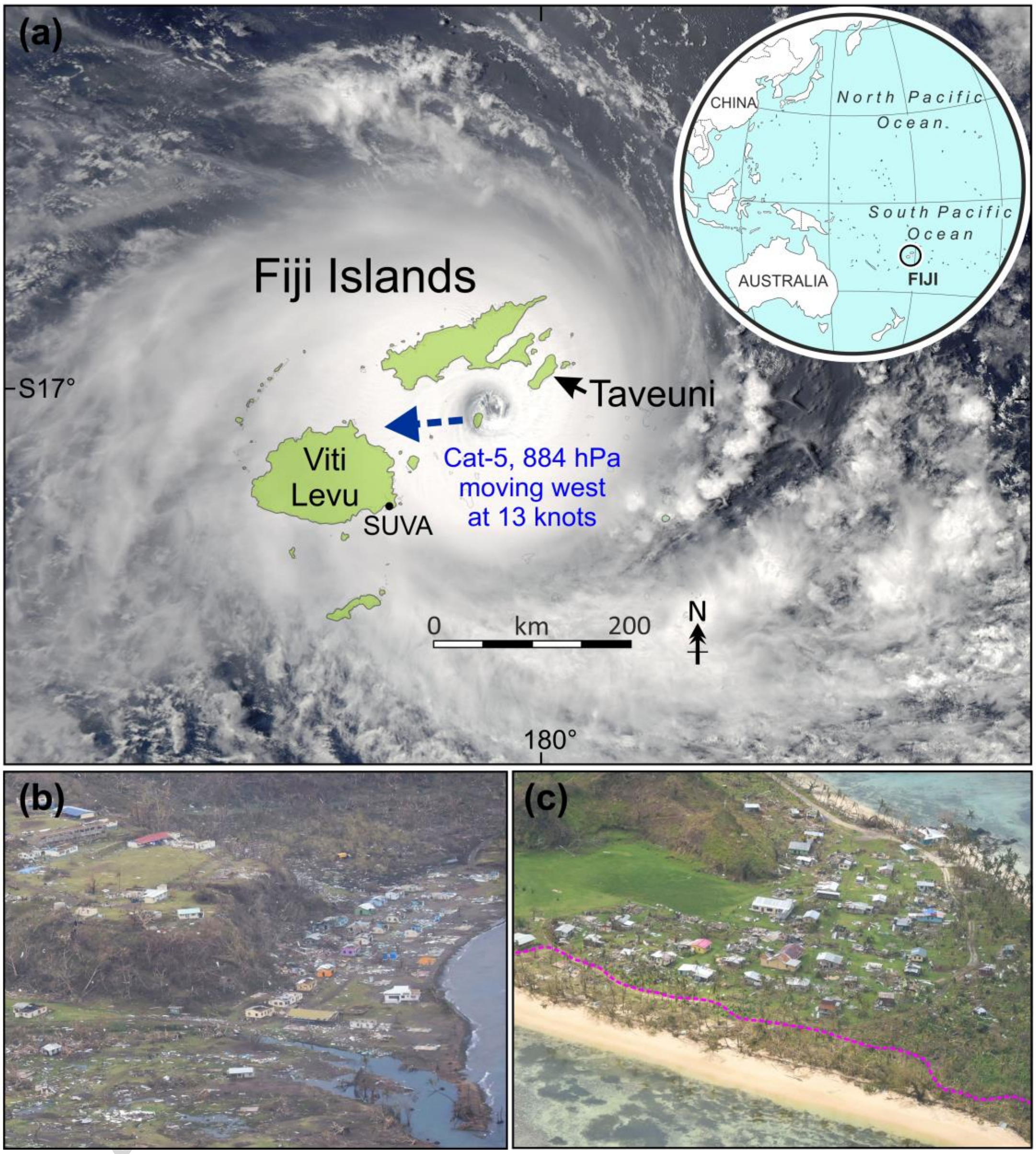

(a)
Fiji Islands
Taveuni
Viti
Levu
SUVA
Cat-5, 884 hPa
moving west
at 13 knots
S17°
180°
0
km
200
N
CHINA
North Pacific
Ocean
South Pacific
Ocean
AUSTRALIA
FIJI
(b)
(c)

Figure 2

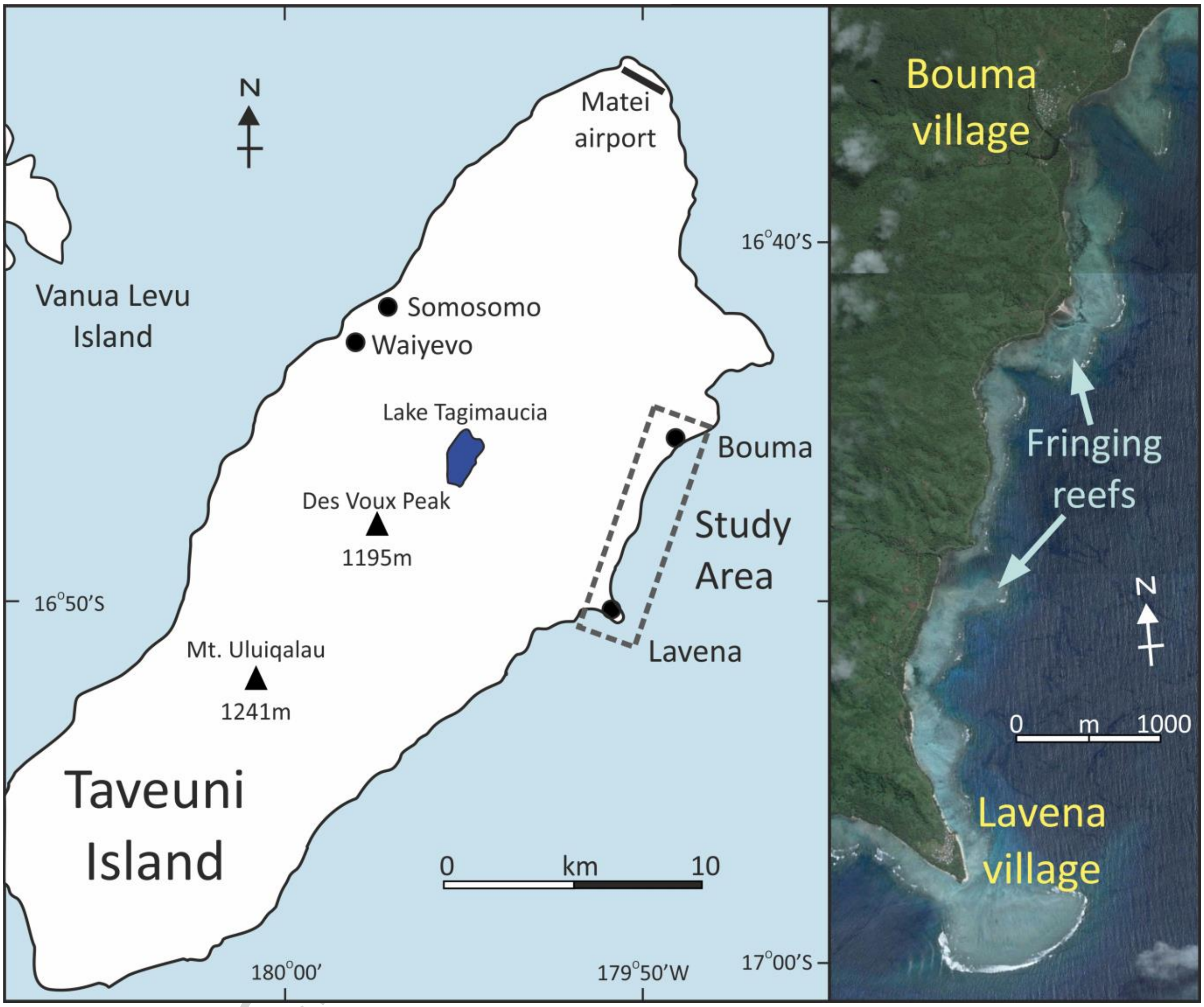

Matei
airport
Vanua Levu
Island
Somosomo
Waiyevo
Lake Tagimaucia
Des Voux Peak
1195m
Bouma
Study
Area
Lavena
Mt. Uluiqalau
1241m
Taveuni
Island
0
km
10
16°40'S
16°50'S
17°00'S
180°00'
179°50'W
N
Bouma
village
Fringing
reefs
N
0
m
1000
Lavena
village

Figure 3

Figure 4

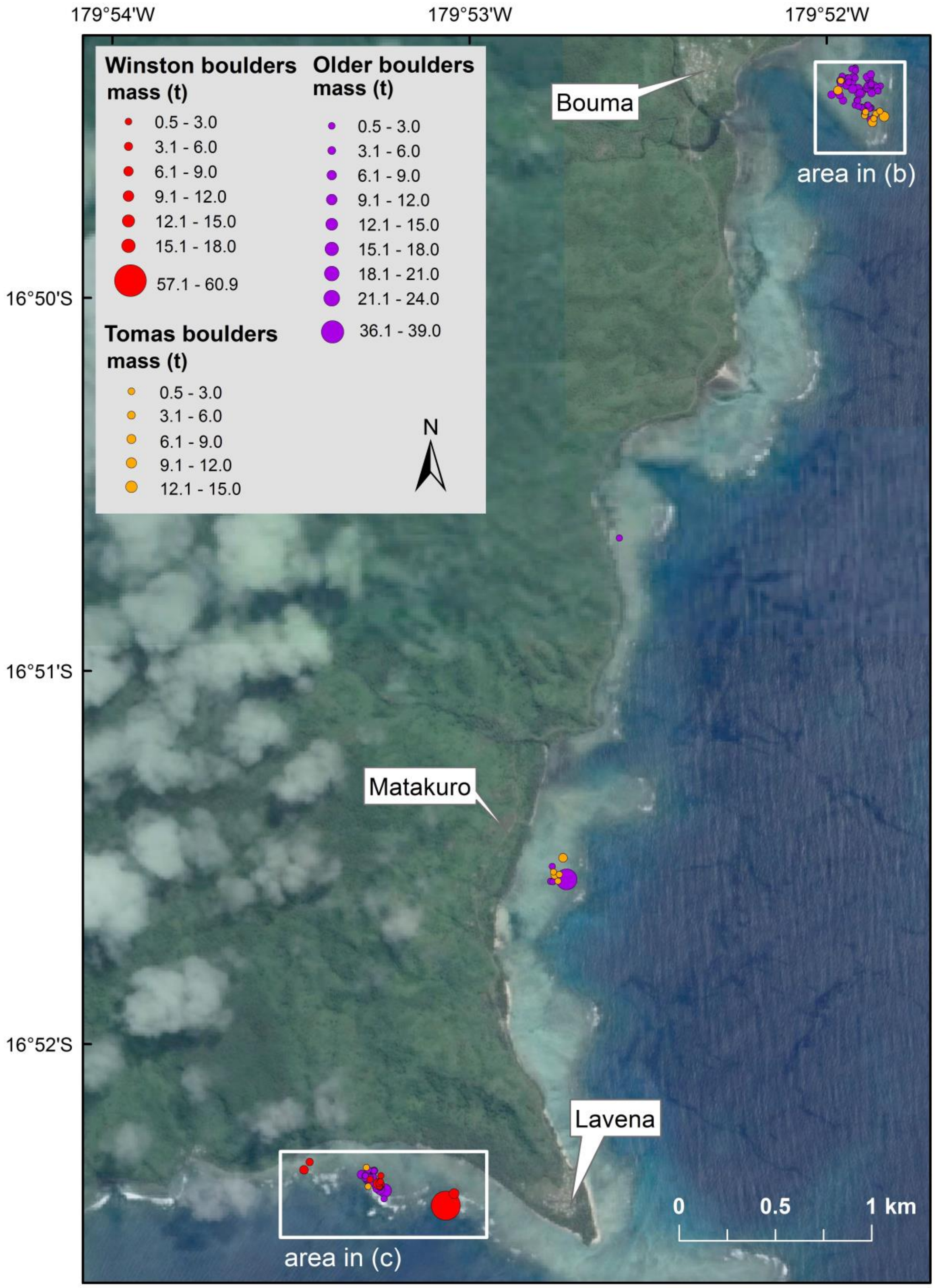

179°54'W
179°53'W
179°52'W
16°50'S
16°51'S
16°52'S
Winston boulders mass (t)
0.5 - 3.0
3.1 - 6.0
6.1 - 9.0
9.1 - 12.0
12.1 - 15.0
15.1 - 18.0
57.1 - 60.9
Older boulders mass (t)
0.5 - 3.0
3.1 - 6.0
6.1 - 9.0
9.1 - 12.0
12.1 - 15.0
15.1 - 18.0
18.1 - 21.0
21.1 - 24.0
36.1 - 39.0
Tomas boulders mass (t)
0.5 - 3.0
3.1 - 6.0
6.1 - 9.0
9.1 - 12.0
12.1 - 15.0
N
Bouma
area in (b)
Matakuro
Lavena
area in (c)
0
0.5
1 km

Figure 5a

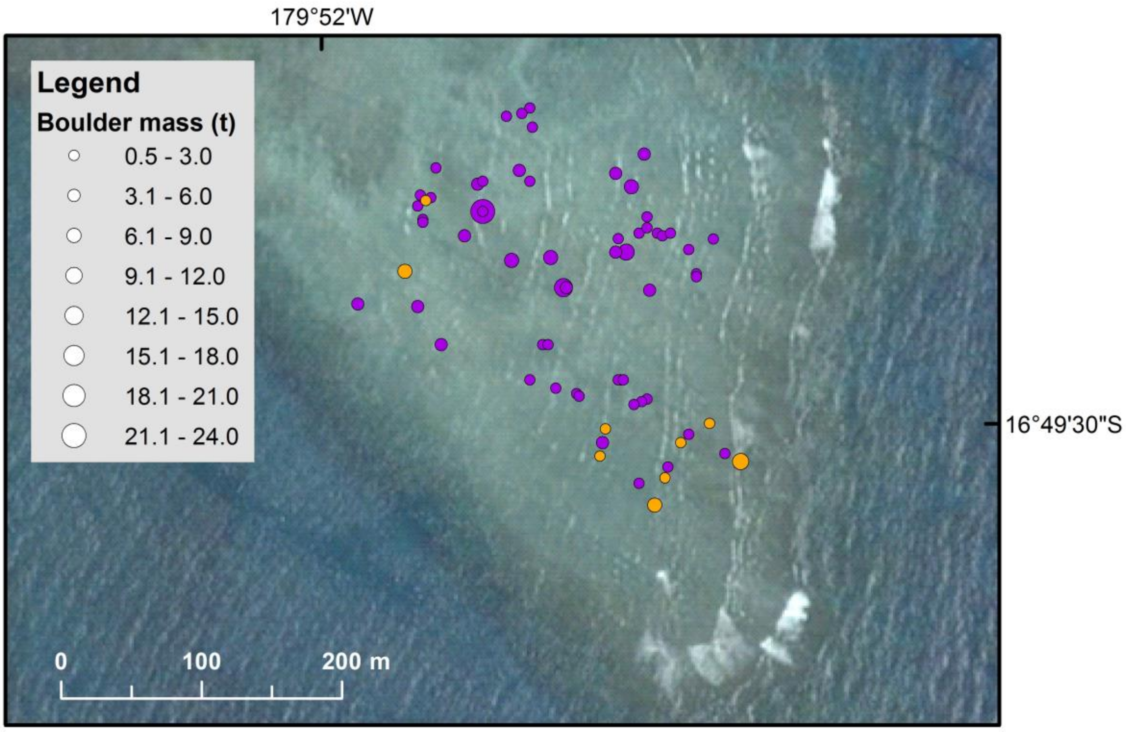

179°52'W
Legend
Boulder mass (t)
0.5 - 3.0
3.1 - 6.0
6.1 - 9.0
9.1 - 12.0
12.1 - 15.0
15.1 - 18.0
18.1 - 21.0
21.1 - 24.0
16°49'30"S
0
100
200 m

Figure 5b

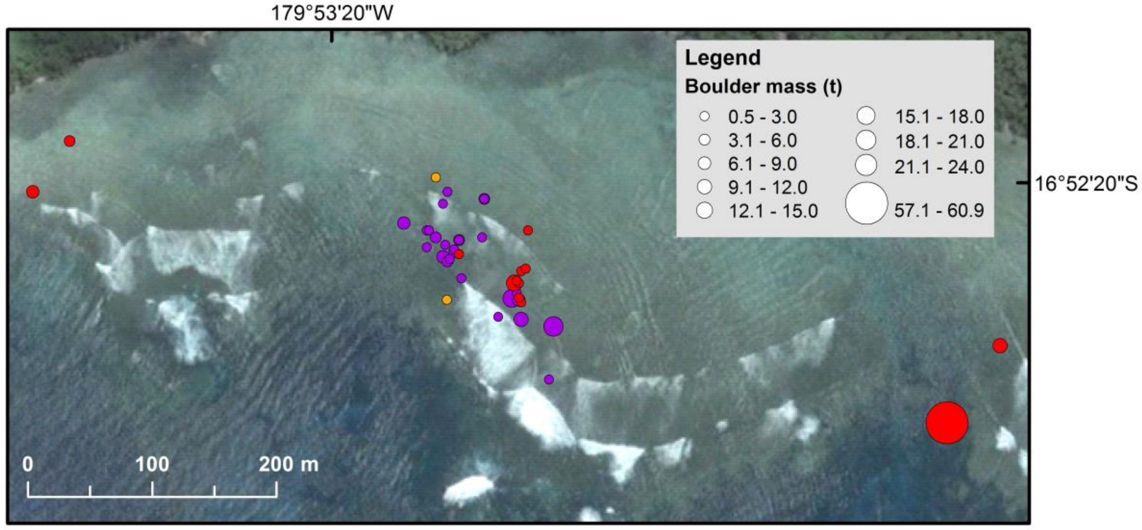
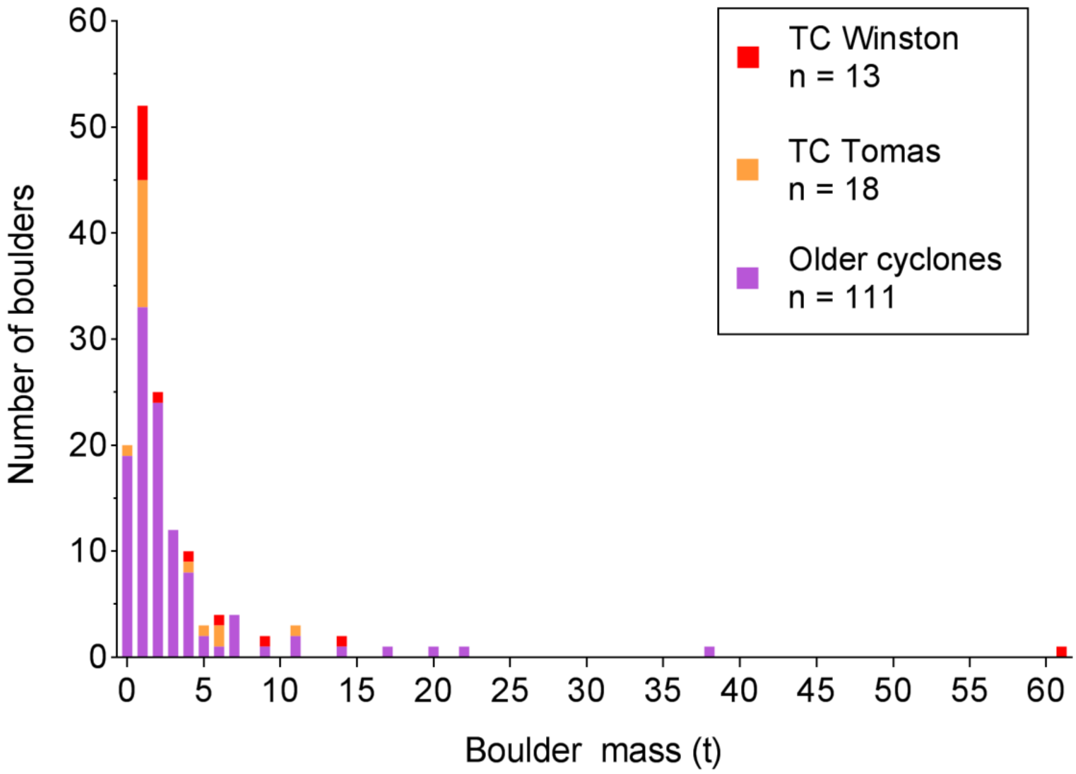
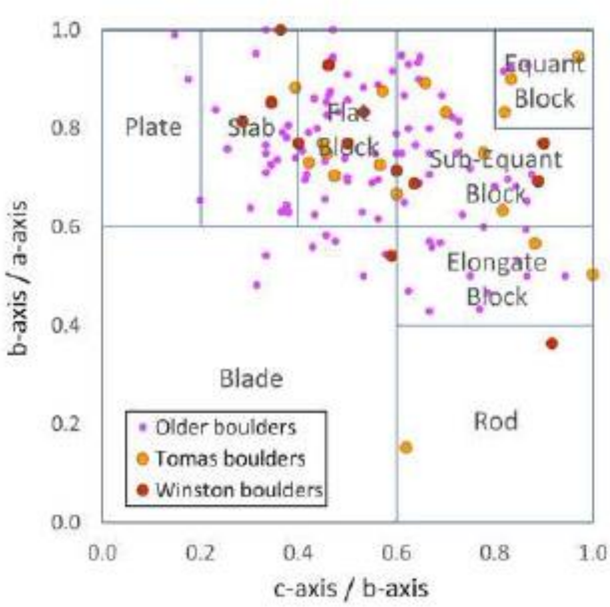

179°53'20"W
16°52'20"S
Legend
Boulder mass (t)
0.5 - 3.0
3.1 - 6.0
6.1 - 9.0
9.1 - 12.0
12.1 - 15.0
15.1 - 18.0
18.1 - 21.0
21.1 - 24.0
57.1 - 60.9
0
100
200 m

Figure 5c



60
50
40
30
20
10
0
Number of boulders
TC Winston
n = 13
TC Tomas
n = 18
Older cyclones
n = 111
0
5
10
15
20
25
30
35
40
45
50
55
60
Boulder mass (t)

Figure 6



1.0
0.8
0.6
0.4
0.2
0.0
b-axis / a-axis
0.0
0.2
0.4
0.6
0.8
1.0
c-axis / b-axis
Plate
Slab
Flat Block
Equant Block
Sub-Equant Block
Elongate Block
Blade
Rod
Older boulders
Tomas boulders
Winston boulders

Figure 7

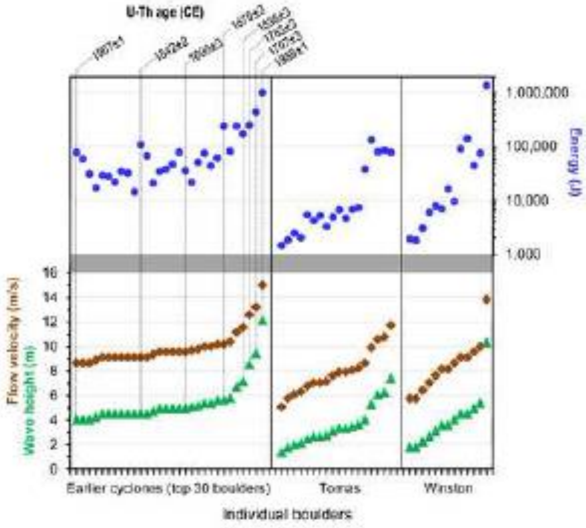

U-Th age (CE)
1,000,000
100,000
10,000
1,000
Energy (J)
16
14
12
10
8
6
4
2
0
Flow velocity (m/s)
Wave height (m)
Earlier cyclones (top 30 boulders)
Tomas
Winston
Individual boulders

Figure 8

Highlights

- Cyclone Winston (February 2016) was the strongest landfalling cyclone on record in the South Pacific.
- On Taveuni island, Fiji, carbonate boulders up to 34 m^3 and 61 tons were deposited on reefs.
- Coastal waves reached over 10 m in height and generated flow velocities exceeding 14 m s^{-1}.
- Comparison is made between Winston, Tomas and prehistorical cyclones.
- Geomorphological evidence suggests similar magnitude events over centennial timescales.